

EVALUATION OF p + ^{29}Si CROSS SECTIONS FOR THE ENERGY
RANGE 1 to 150 MeV

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This evaluation provides a complete representation of the nuclear data needed for transport, damage, heating, radioactivity, and shielding applications over the incident proton energy range from 1 to 150 MeV. The evaluation utilizes MF=6, MT=5 to represent all reaction data. Production cross sections and emission spectra are given for neutrons, protons, deuterons, tritons, alpha particles, gamma rays, and all residual nuclides produced ($A > 5$) in the reaction chains. To summarize, the ENDF sections with non-zero data above are:

MF=3 MT= 2 Integral of nuclear plus interference components of the elastic scattering cross section

MT= 5 Sum of binary (p,n') and (p,x) reactions

MF=6 MT= 2 Elastic (p,p) angular distributions given as ratios of the differential nuclear-plus-interference to the integrated value.

MT= 5 Production cross sections and energy-angle distributions for emission neutrons, protons, deuterons, and alphas; and angle-integrated spectra for gamma rays and residual nuclei that are stable against particle emission

The evaluation is based on nuclear model calculations that have been benchmarked to experimental data, especially for $n + \text{Si}^{28}$ and $p + \text{Si}^{28}$ reactions (Ch97). We use the GNASH code system (Yo92), which utilizes Hauser-Feshbach statistical, preequilibrium and direct-reaction theories. Spherical optical model calculations are used to obtain particle transmission coefficients for the Hauser-Feshbach calculations, as well as for the elastic proton angular distributions.

Cross sections and spectra for producing individual residual nuclei are included for reactions. The energy-angle-correlations for all outgoing particles are based on Kalbach systematics (Ka88).

A model was developed to calculate the energy distributions of all recoil nuclei in the GNASH calculations (Ch96). The recoil energy distributions are represented in the laboratory system in MT=5, MF=6, and are given as isotropic in the lab system. All other data in MT=5, MF=6 are given in the center-of-mass system. This method of representation utilizes the LCT=3 option approved at the November, 1996, CSEWG meeting.

Preequilibrium corrections were performed in the course of the GNASH calculations using the exciton model of Kalbach (Ka77,

Ka85), validated by comparison with calculations using Feshbach, Kerman, Koonin (FKK) theory [Ch93]. Discrete level data from nuclear data sheets were matched to continuum level densities using the formulation of Ignatyuk (Ig75) and pairing and shell parameters from the Cook (Co67) analysis. Neutron and charged-particle transmission coefficients were obtained from the optical potentials, as discussed below. Gamma-ray transmission coefficients were calculated using the Kopecky-Uhl model (Ko90).

DETAILS OF THE p + Si-29 ANALYSIS

The Madland global medium-energy optical potential (Ma88) was used for neutrons above 46 MeV, and the Wilmore-Hodgson (Wi64) potential was used for lower neutron energies. The Madland global medium-energy optical potential was used for protons above 28 MeV, and the Becchetti-Greenlees (Be69) potential was used for lower proton energies. In both cases the transition region to the Madland potential was chosen to approximately give continuity in the reaction cross section. For deuterons, the Perey global potential was used; for alpha particles the MacFadden (Ma66) potential was used; and for tritons the Becchetti-Greenlees (Be71) potential was used.

While the above optical potentials did describe the experimental proton nonelastic cross section data fairly well, we modified the theoretical predictions slightly to better agree with the measurements, and renormalized the transmission coefficients accordingly. In addition to using Si nonelastic proton cross section measurements, we also were guided by p+Al nonelastic data, scaled by $A^{**2/3}$. The Si-29 nonelastic cross section was taken by scaling the evaluated Si-28 value by 1.02036 (an $A^{**2/3}$ factor).

Above 20 MeV, the same proton inelastic cross sections were used as for n+Si29 (the 3/2+ and 5/2+ levels - this is a reasonable approximation for energies well above the Coulomb barrier) - see our n+29Si ENDF file-1 documentation. At lower energies the 20-MeV cross sections were modified according to the shape obtained from our coupled-channel calculations for p+28Si. This approximate treatment is sufficiently accurate for most applications due to the small relative abundance of 29-Si.

The same preequilibrium input parameters were used as for Si-28, which was benchmarked, indirectly, by comparing neutron-induced calculated cross sections against (n,xz) data from the Louvain group at 63 MeV, and against unpublished (n,xp) data by Haight et al. for neutrons up to 50 MeV. See our ENDF file-1 for p+28Si for more details.

REFERENCES

[Be69]. F.D. Becchetti, Jr., and G.W. Greenlees, Phys. Rev. 182, 1190 (1969).

[Be71]. F.D. Becchetti, Jr., and G.W. Greenlees in "Polarization Phenomena in Nuclear Reactions," (Ed: H.H. Barschall and W. Haeberli, The University of Wisconsin Press, 1971) p.682.

[Ch93]. M. B. Chadwick and P. G. Young, "Feshbach-Kerman-Koonin

Analysis of ^{93}Nb Reactions: P \rightarrow Q Transitions and Reduced Importance of Multistep Compound Emission," Phys. Rev. C 47, 2255 (1993).

[Ch96]. M. B. Chadwick, P. G. Young, R. E. MacFarlane, and A. J. Koning, "High-Energy Nuclear Data Libraries for Accelerator-Driven Technologies: Calculational Method for Heavy Recoils," Proc. of 2nd Int. Conf. on Accelerator Driven Transmutation Technology and Applications, Kalmar, Sweden, 3-7 June 1996.

[Ch97]. M. B. Chadwick and P. G. Young, "GNASH Calculations of n, p + Si isotopes and Benchmarking of Results" in APT PROGRESS REPORT: 1 June - 1 July 1997, internal Los Alamos National Laboratory memo T-2-97/MS-43, 7 July 1997 from R.E. MacFarlane to L. Waters.

[Ma66]. L. MacFadden and G. R. Satchler, Nucl. Phys. 84, 177 (1966).

[Ma88]. D.G. Madland, "Recent Results in the Development of a Global Medium-Energy Nucleon-Nucleus Optical-Model Potential," Proc. OECD/NEANDC Specialist's Mtg. on Preequilibrium Nuclear Reactions, Semmering, Austria, 10-12 Feb. 1988, NEANDC-245 'U' (1988).

[Pe63]. C. M. Perey and F. G. Perey, Phys. Rev. 132, 755 (1963).

[Wi64]. D. Wilmore and P. E. Hodgson, "The Calculation of Neutron Cross Sections from Optical Potentials," Nucl. Phys. 55, 673 (1964).

[Yo92]. P. G. Young, E. D. Arthur, and M. B. Chadwick, "Comprehensive Nuclear Model Calculations: Introduction to the Theory and Use of the GNASH Code," LA-12343-MS (1992).

14029 = TARGET 1000Z+A (if A=0 then elemental)

1001 = PROJECTILE 1000Z+A

Nonelastic, elastic, and Production cross sections for A<5 ejectiles in barns:

Energy	nonelas	elastic	neutron	proton	deuteron	triton	helium3	alpha	gamma
2.000E+00	1.189E-03	0.000E+00	0.000E+00	1.189E-03	0.000E+00	0.000E+00	0.000E+00	0.000E+00	1.189E-03
3.000E+00	6.729E-02	0.000E+00	0.000E+00	6.728E-02	0.000E+00	0.000E+00	0.000E+00	0.000E+00	6.731E-02
4.000E+00	3.013E-01	0.000E+00	0.000E+00	3.013E-01	0.000E+00	0.000E+00	0.000E+00	0.000E+00	3.022E-01
5.000E+00	4.763E-01	0.000E+00	0.000E+00	4.762E-01	0.000E+00	0.000E+00	0.000E+00	0.000E+00	5.069E-01
6.000E+00	6.092E-01	0.000E+00	1.297E-02	5.962E-01	0.000E+00	0.000E+00	0.000E+00	0.000E+00	7.288E-01
7.000E+00	7.106E-01	0.000E+00	5.032E-02	6.602E-01	1.144E-07	0.000E+00	0.000E+00	1.009E-05	9.289E-01
8.000E+00	7.869E-01	0.000E+00	8.188E-02	7.033E-01	1.118E-03	0.000E+00	0.000E+00	6.082E-04	1.170E+00
9.000E+00	8.351E-01	0.000E+00	1.113E-01	7.124E-01	4.443E-03	0.000E+00	0.000E+00	6.937E-03	1.370E+00
1.000E+01	8.625E-01	0.000E+00	1.216E-01	7.091E-01	9.074E-03	0.000E+00	0.000E+00	2.312E-02	1.517E+00
1.100E+01	8.759E-01	0.000E+00	1.293E-01	6.997E-01	1.498E-02	0.000E+00	0.000E+00	4.387E-02	1.621E+00
1.200E+01	8.831E-01	0.000E+00	1.702E-01	6.879E-01	1.994E-02	0.000E+00	0.000E+00	6.234E-02	1.639E+00
1.300E+01	8.904E-01	0.000E+00	2.305E-01	6.865E-01	2.430E-02	0.000E+00	0.000E+00	8.454E-02	1.590E+00
1.400E+01	8.973E-01	0.000E+00	2.991E-01	7.012E-01	2.912E-02	0.000E+00	0.000E+00	8.984E-02	1.513E+00
1.500E+01	9.011E-01	0.000E+00	3.624E-01	7.170E-01	3.512E-02	0.000E+00	0.000E+00	8.588E-02	1.431E+00
1.600E+01	9.009E-01	0.000E+00	4.094E-01	7.273E-01	4.180E-02	0.000E+00	0.000E+00	8.295E-02	1.367E+00
1.700E+01	8.967E-01	0.000E+00	4.497E-01	7.373E-01	4.889E-02	0.000E+00	0.000E+00	7.886E-02	1.294E+00
1.800E+01	8.900E-01	0.000E+00	4.694E-01	7.518E-01	5.498E-02	0.000E+00	0.000E+00	7.400E-02	1.241E+00
1.900E+01	8.806E-01	0.000E+00	4.757E-01	7.644E-01	5.931E-02	6.317E-06	0.000E+00	7.130E-02	1.203E+00
2.000E+01	8.703E-01	0.000E+00	4.718E-01	7.730E-01	6.252E-02	8.360E-05	0.000E+00	7.127E-02	1.168E+00
2.200E+01	8.476E-01	0.000E+00	4.579E-01	7.819E-01	6.933E-02	3.064E-04	0.000E+00	7.854E-02	1.158E+00
2.400E+01	8.244E-01	0.000E+00	4.405E-01	7.911E-01	7.401E-02	4.949E-04	0.000E+00	9.036E-02	1.150E+00
2.600E+01	8.007E-01	0.000E+00	4.129E-01	8.006E-01	7.623E-02	5.579E-04	0.000E+00	1.156E-01	1.098E+00
2.800E+01	7.680E-01	0.000E+00	4.050E-01	7.909E-01	7.953E-02	7.764E-04	0.000E+00	1.200E-01	1.032E+00
3.000E+01	7.412E-01	0.000E+00	4.009E-01	7.857E-01	8.095E-02	9.402E-04	0.000E+00	1.212E-01	9.800E-01
3.500E+01	7.022E-01	0.000E+00	4.201E-01	7.854E-01	8.211E-02	1.684E-03	0.000E+00	1.210E-01	9.030E-01
4.000E+01	6.657E-01	0.000E+00	4.327E-01	7.871E-01	8.099E-02	2.495E-03	0.000E+00	1.196E-01	8.609E-01
4.500E+01	6.271E-01	0.000E+00	4.346E-01	7.910E-01	7.666E-02	3.188E-03	0.000E+00	1.332E-01	8.081E-01
5.000E+01	5.889E-01	0.000E+00	4.350E-01	7.879E-01	7.364E-02	3.780E-03	0.000E+00	1.293E-01	7.642E-01
5.500E+01	5.566E-01	0.000E+00	4.391E-01	7.821E-01	7.235E-02	4.374E-03	0.000E+00	1.273E-01	7.325E-01
6.000E+01	5.293E-01	0.000E+00	4.460E-01	7.806E-01	7.029E-02	5.012E-03	0.000E+00	1.363E-01	6.981E-01
6.500E+01	5.125E-01	0.000E+00	4.506E-01	7.897E-01	6.964E-02	5.615E-03	0.000E+00	1.372E-01	6.810E-01
7.000E+01	4.998E-01	0.000E+00	4.757E-01	8.020E-01	7.054E-02	6.271E-03	0.000E+00	1.403E-01	6.512E-01
7.500E+01	4.877E-01	0.000E+00	4.904E-01	8.085E-01	7.129E-02	6.940E-03	0.000E+00	1.443E-01	6.392E-01
8.000E+01	4.766E-01	0.000E+00	5.049E-01	8.156E-01	7.229E-02	7.824E-03	0.000E+00	1.532E-01	6.169E-01
8.500E+01	4.663E-01	0.000E+00	5.193E-01	8.262E-01	7.098E-02	8.639E-03	0.000E+00	1.566E-01	6.051E-01
9.000E+01	4.569E-01	0.000E+00	5.316E-01	8.354E-01	7.087E-02	9.514E-03	0.000E+00	1.613E-01	5.906E-01
9.500E+01	4.487E-01	0.000E+00	5.442E-01	8.425E-01	7.238E-02	1.047E-02	0.000E+00	1.646E-01	5.735E-01
1.000E+02	4.413E-01	0.000E+00	5.488E-01	8.428E-01	7.336E-02	1.086E-02	0.000E+00	1.611E-01	5.625E-01
1.100E+02	4.293E-01	0.000E+00	5.684E-01	8.511E-01	7.630E-02	1.290E-02	0.000E+00	1.679E-01	5.383E-01
1.200E+02	4.210E-01	0.000E+00	5.925E-01	8.744E-01	7.701E-02	1.522E-02	0.000E+00	1.749E-01	5.222E-01
1.300E+02	4.166E-01	0.000E+00	6.175E-01	8.969E-01	8.101E-02	1.764E-02	0.000E+00	1.797E-01	5.063E-01
1.400E+02	4.164E-01	0.000E+00	6.445E-01	9.202E-01	8.554E-02	2.033E-02	0.000E+00	1.851E-01	4.961E-01
1.500E+02	4.200E-01	0.000E+00	6.771E-01	9.608E-01	8.826E-02	2.330E-02	0.000E+00	1.920E-01	4.949E-01

14029 = TARGET 1000Z+A (if A=0 then elemental)

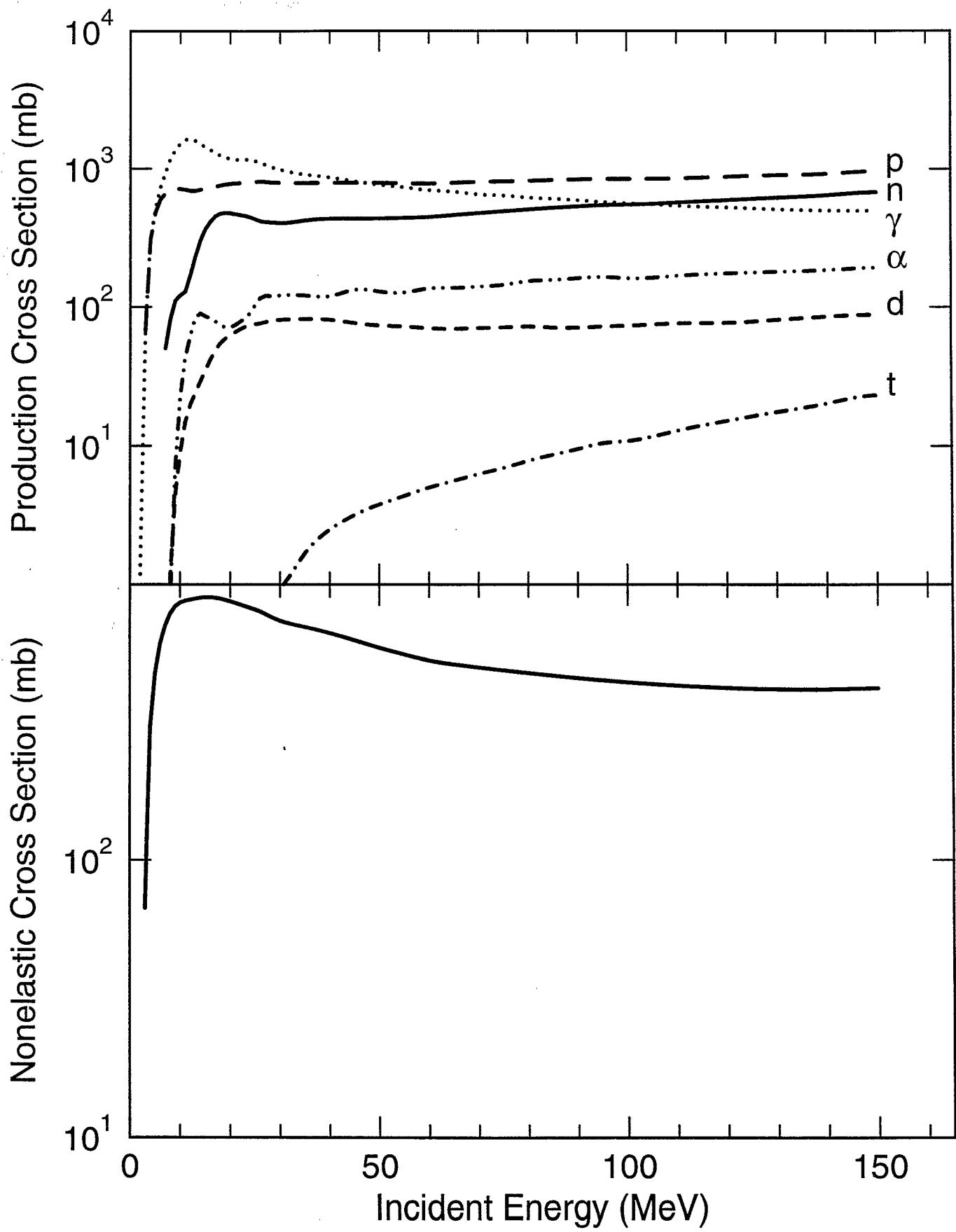
1001 = PROJECTILE 1000Z+A

Aver. lab emission energies for A<5 ejectiles in MeV:

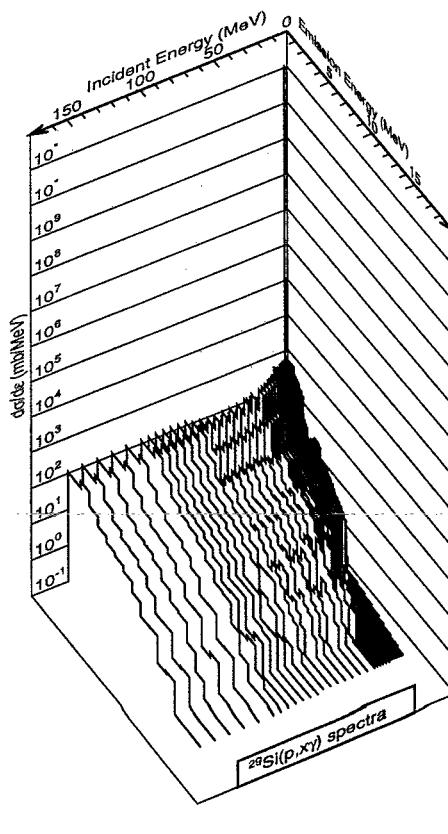
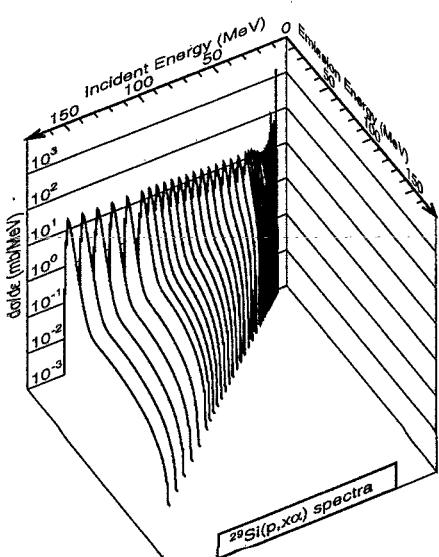
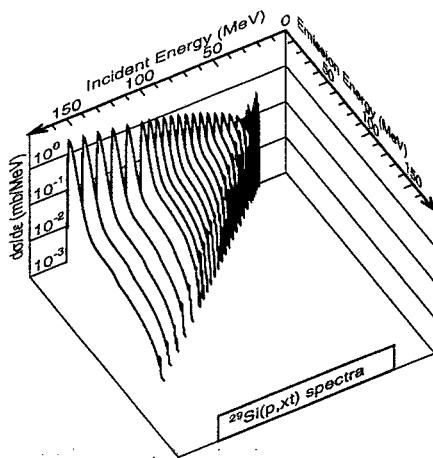
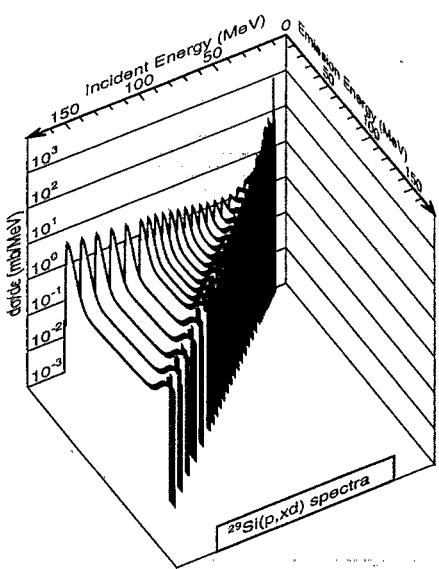
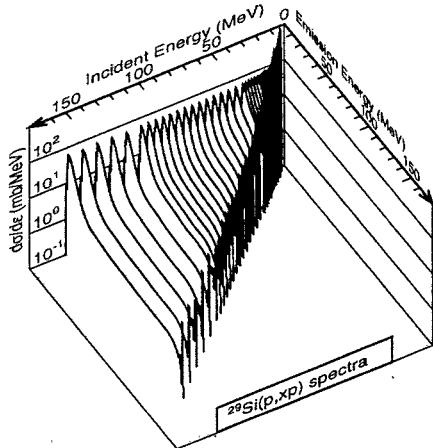
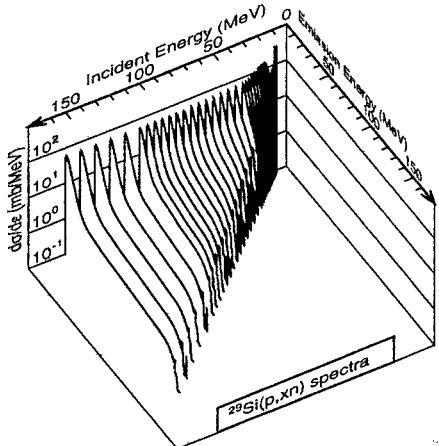
Energy	neutron	proton	deuteron	triton	helium3	alpha	gamma
2.000E+00	0.000E+00	2.260E-03	0.000E+00	0.000E+00	0.000E+00	0.000E+00	5.000E-12
3.000E+00	0.000E+00	1.645E+00	0.000E+00	0.000E+00	0.000E+00	0.000E+00	1.292E+00
4.000E+00	0.000E+00	2.239E+00	0.000E+00	0.000E+00	0.000E+00	0.000E+00	1.452E+00
5.000E+00	0.000E+00	2.918E+00	0.000E+00	0.000E+00	0.000E+00	0.000E+00	1.675E+00
6.000E+00	4.179E-02	3.546E+00	0.000E+00	0.000E+00	0.000E+00	0.000E+00	1.713E+00
7.000E+00	9.335E-01	4.102E+00	4.320E-01	0.000E+00	0.000E+00	1.518E+00	1.791E+00
8.000E+00	1.144E+00	4.482E+00	1.353E+00	0.000E+00	0.000E+00	2.414E+00	1.907E+00
9.000E+00	1.508E+00	4.822E+00	2.261E+00	0.000E+00	0.000E+00	3.220E+00	2.024E+00
1.000E+01	1.975E+00	5.225E+00	2.798E+00	0.000E+00	0.000E+00	3.869E+00	2.127E+00
1.100E+01	2.215E+00	5.525E+00	3.160E+00	0.000E+00	0.000E+00	4.407E+00	2.226E+00
1.200E+01	2.013E+00	5.869E+00	3.774E+00	0.000E+00	0.000E+00	4.769E+00	2.239E+00
1.300E+01	1.852E+00	6.130E+00	4.300E+00	0.000E+00	0.000E+00	5.110E+00	2.203E+00
1.400E+01	1.803E+00	6.374E+00	4.693E+00	0.000E+00	0.000E+00	5.518E+00	2.177E+00
1.500E+01	1.946E+00	6.665E+00	5.100E+00	0.000E+00	0.000E+00	5.877E+00	2.165E+00
1.600E+01	2.166E+00	6.986E+00	5.492E+00	0.000E+00	0.000E+00	6.186E+00	2.175E+00
1.700E+01	2.387E+00	7.258E+00	5.992E+00	0.000E+00	0.000E+00	6.442E+00	2.176E+00
1.800E+01	2.622E+00	7.543E+00	6.435E+00	0.000E+00	0.000E+00	6.626E+00	2.191E+00
1.900E+01	2.758E+00	7.850E+00	6.995E+00	1.106E+00	0.000E+00	6.701E+00	2.219E+00
2.000E+01	2.971E+00	8.185E+00	7.620E+00	1.777E+00	0.000E+00	6.662E+00	2.391E+00
2.200E+01	3.425E+00	8.675E+00	8.653E+00	3.158E+00	0.000E+00	6.574E+00	2.497E+00
2.400E+01	3.769E+00	9.078E+00	9.784E+00	4.027E+00	0.000E+00	6.548E+00	2.583E+00
2.600E+01	4.273E+00	9.407E+00	1.093E+01	4.810E+00	0.000E+00	6.667E+00	2.565E+00
2.800E+01	4.723E+00	9.807E+00	1.208E+01	5.631E+00	0.000E+00	6.816E+00	2.588E+00

3.000E+01	5.115E+00	1.031E+01	1.324E+01	6.602E+00	0.000E+00	7.021E+00	2.602E+00
3.500E+01	6.201E+00	1.174E+01	1.653E+01	8.355E+00	0.000E+00	7.429E+00	2.625E+00
4.000E+01	7.148E+00	1.284E+01	1.997E+01	9.620E+00	0.000E+00	7.936E+00	2.674E+00
4.500E+01	8.051E+00	1.347E+01	2.313E+01	1.049E+01	0.000E+00	8.230E+00	2.646E+00
5.000E+01	9.027E+00	1.443E+01	2.631E+01	1.143E+01	0.000E+00	8.329E+00	2.630E+00
5.500E+01	9.820E+00	1.537E+01	2.936E+01	1.203E+01	0.000E+00	8.514E+00	2.608E+00
6.000E+01	1.052E+01	1.604E+01	3.196E+01	1.227E+01	0.000E+00	8.645E+00	2.545E+00
6.500E+01	1.129E+01	1.691E+01	3.455E+01	1.264E+01	0.000E+00	8.723E+00	2.546E+00
7.000E+01	1.199E+01	1.767E+01	3.698E+01	1.280E+01	0.000E+00	8.785E+00	2.491E+00
7.500E+01	1.268E+01	1.845E+01	3.933E+01	1.290E+01	0.000E+00	8.898E+00	2.483E+00
8.000E+01	1.329E+01	1.905E+01	4.133E+01	1.274E+01	0.000E+00	9.029E+00	2.442E+00
8.500E+01	1.398E+01	1.983E+01	4.284E+01	1.267E+01	0.000E+00	9.126E+00	2.452E+00
9.000E+01	1.467E+01	2.059E+01	4.402E+01	1.250E+01	0.000E+00	9.137E+00	2.465E+00
9.500E+01	1.521E+01	2.134E+01	4.587E+01	1.228E+01	0.000E+00	9.171E+00	2.471E+00
1.000E+02	1.610E+01	2.237E+01	4.831E+01	1.230E+01	0.000E+00	9.145E+00	2.480E+00
1.100E+02	1.739E+01	2.385E+01	5.150E+01	1.183E+01	0.000E+00	9.372E+00	2.452E+00
1.200E+02	1.864E+01	2.531E+01	5.262E+01	1.143E+01	0.000E+00	9.520E+00	2.483E+00
1.300E+02	1.980E+01	2.669E+01	5.520E+01	1.110E+01	0.000E+00	9.633E+00	2.510E+00
1.400E+02	2.101E+01	2.810E+01	5.740E+01	1.085E+01	0.000E+00	9.880E+00	2.491E+00
1.500E+02	2.222E+01	2.954E+01	5.740E+01	1.069E+01	0.000E+00	1.005E+01	2.529E+00

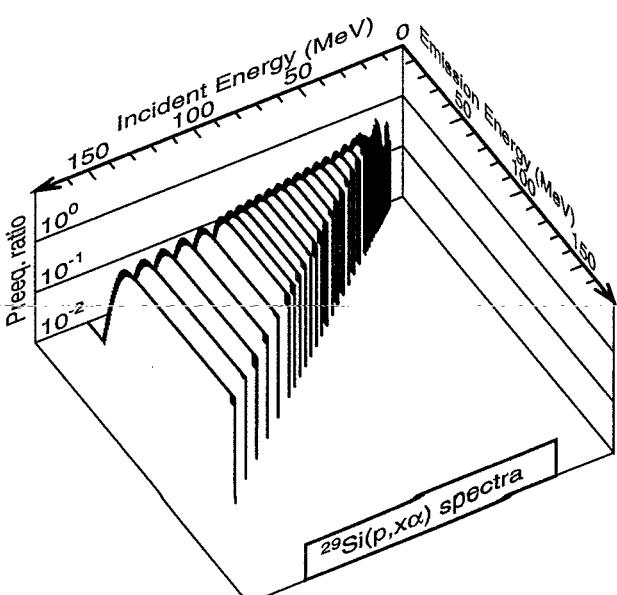
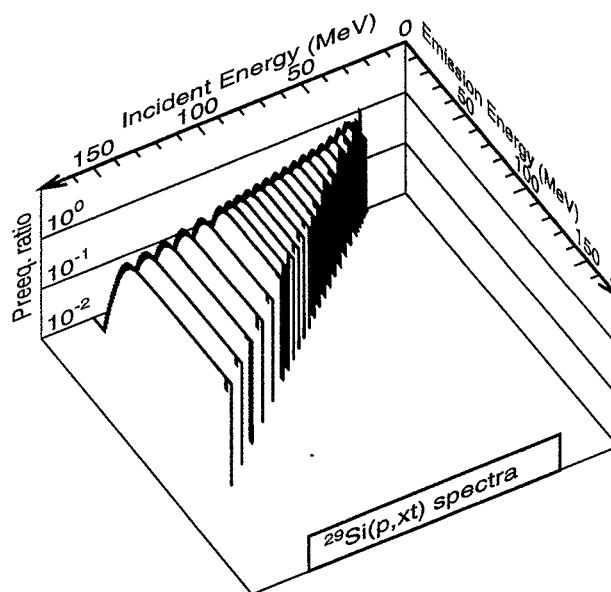
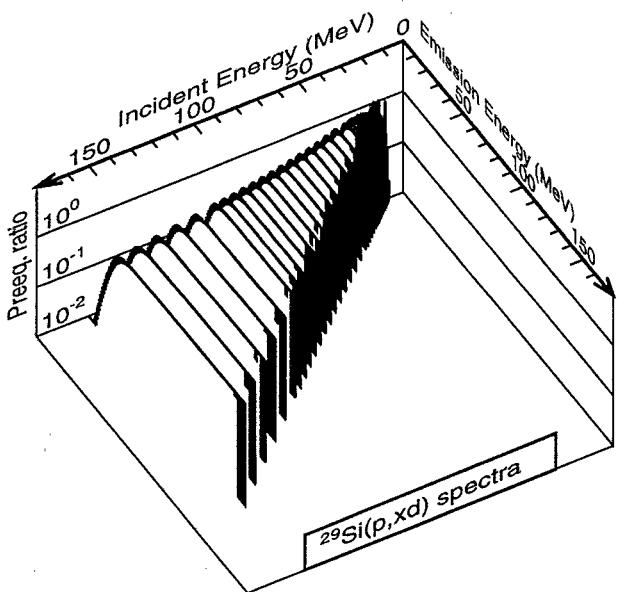
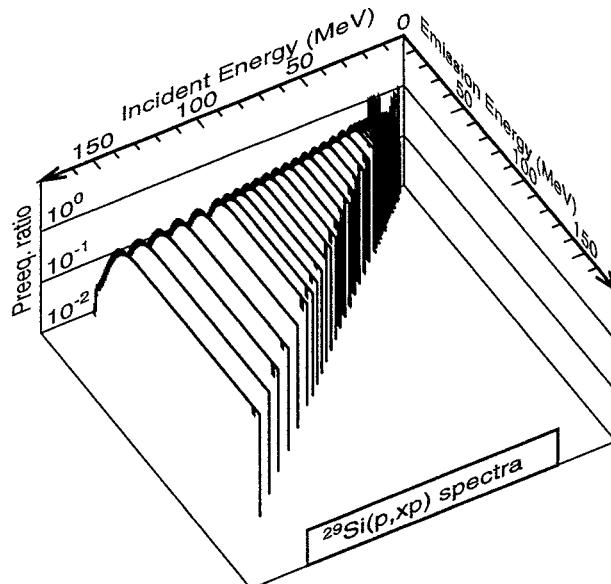
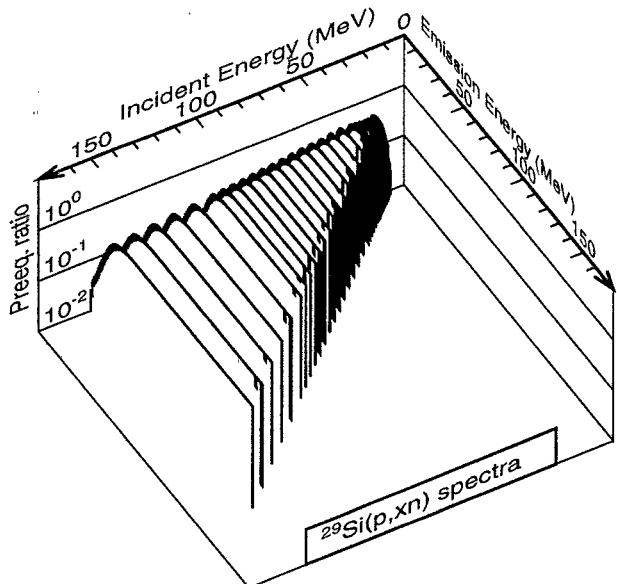
$p + {}^{29}\text{Si}$ nonelastic and production cross sections



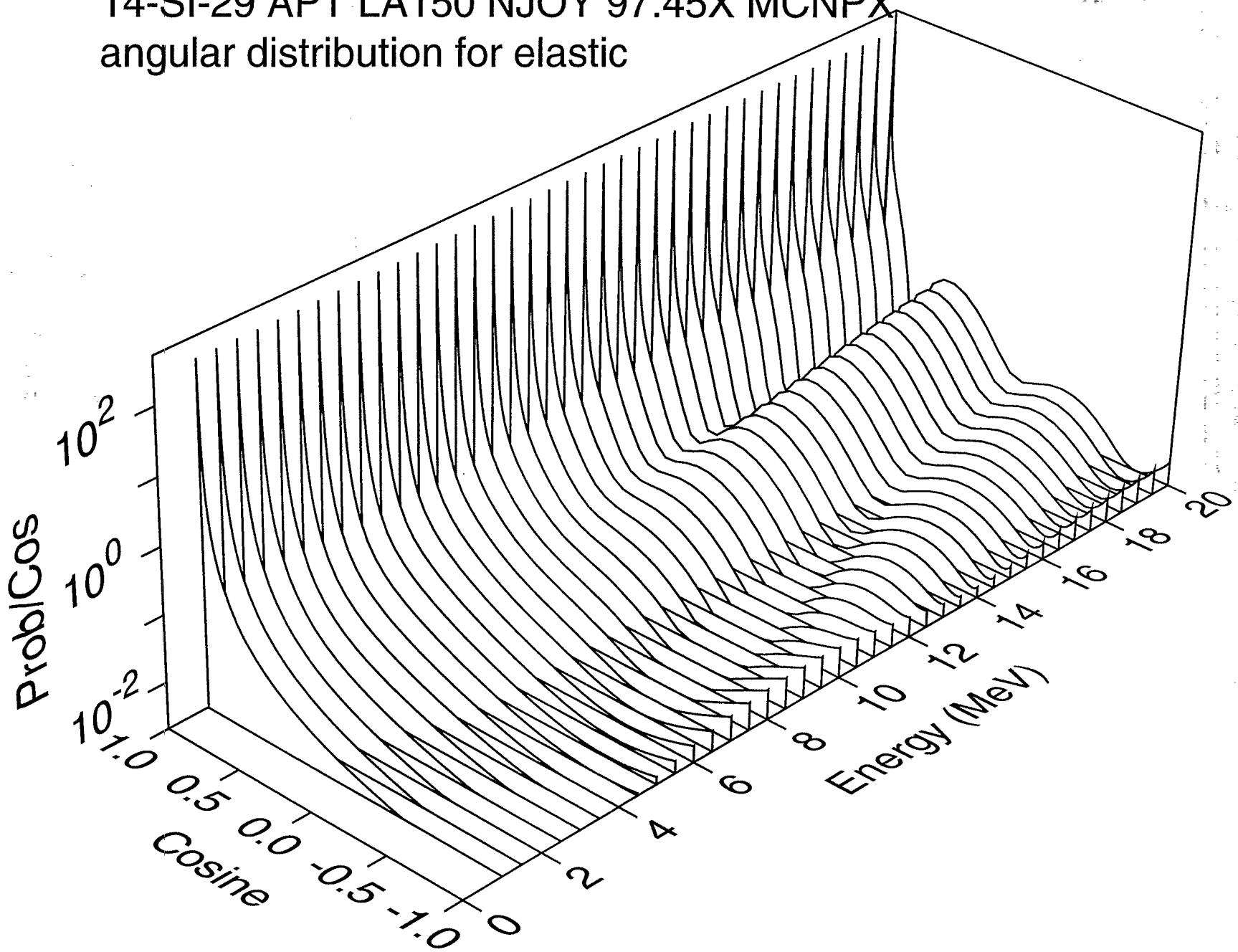
$p + {}^{29}\text{Si}$ angle-integrated emission spectra



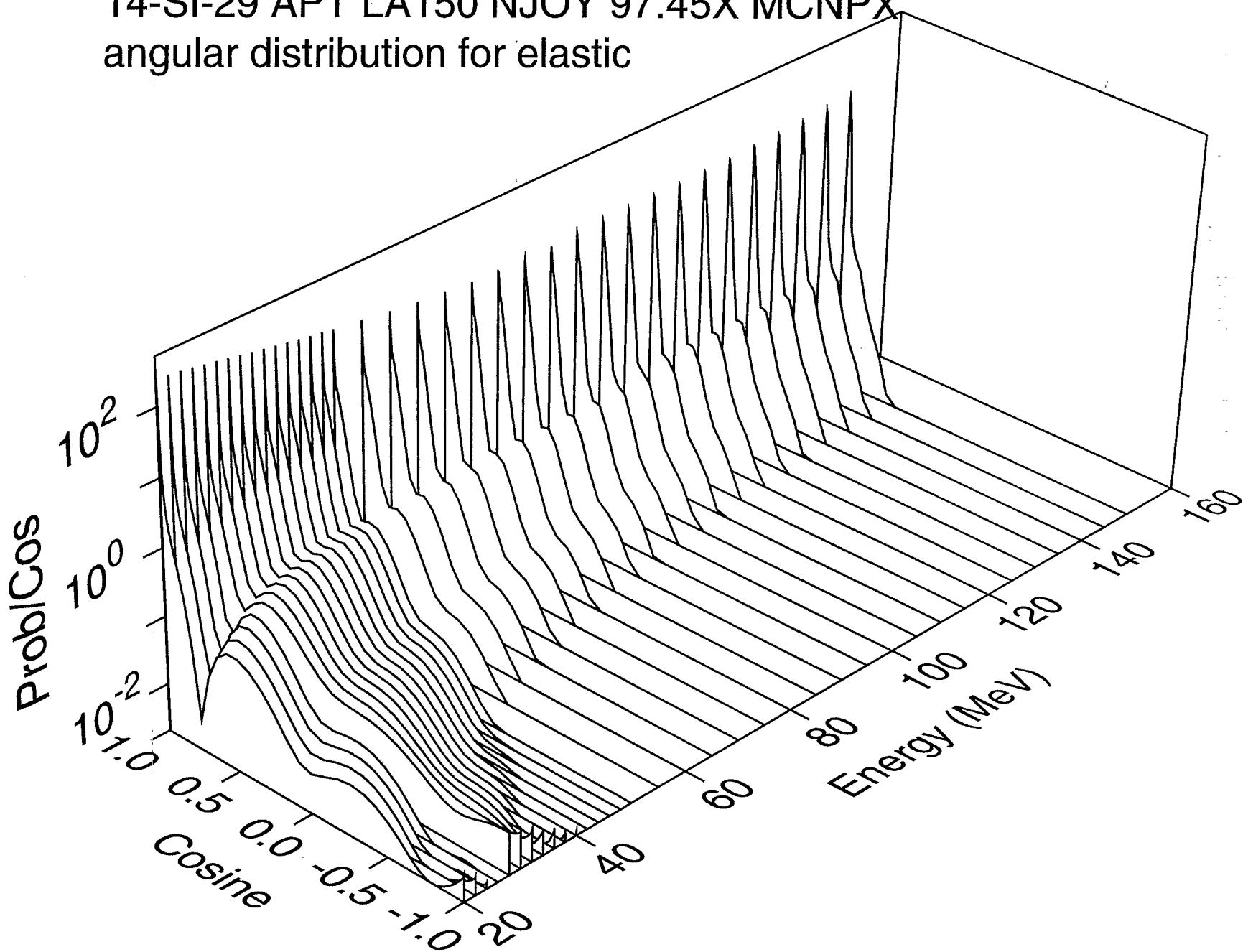
$p + {}^{29}\text{Si}$ Kalbach preequilibrium ratios



14-SI-29 APT LA150 NJOY 97.45X MCNPX
angular distribution for elastic



14-SI-29 APT LA150 NJOY 97.45X MCNPX
angular distribution for elastic



14-SI-29 APT LA150 NJOY 97.45X MCNPX

Heating

